AD-A102 419   DAVID W TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CE--ETC   F/G 20/3
STABILITY CHARACTERISTICS OF EPOXY-IMPREGNATED SUPERCONDUCTING --ETC(U)
JUN 81   D J WALTMAN, M J SUPERCZYNSKI
UNCLASSIFIED   DTNSRDC/PAS-80/42   NL

1 of 1
AD
A102419

END
DATE
FILMED
9 81
DTIC

LEVEL II (12)

DTNSRDC/PAS-80/42

AD A102419

DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Maryland 20084

STABILITY CHARACTERISTICS OF
EPOXY-IMPREGNATED SUPERCONDUCTING
MAGNETS

by

D. J. Waltman, M. J. Superczynski, and
F. E. McDonald

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

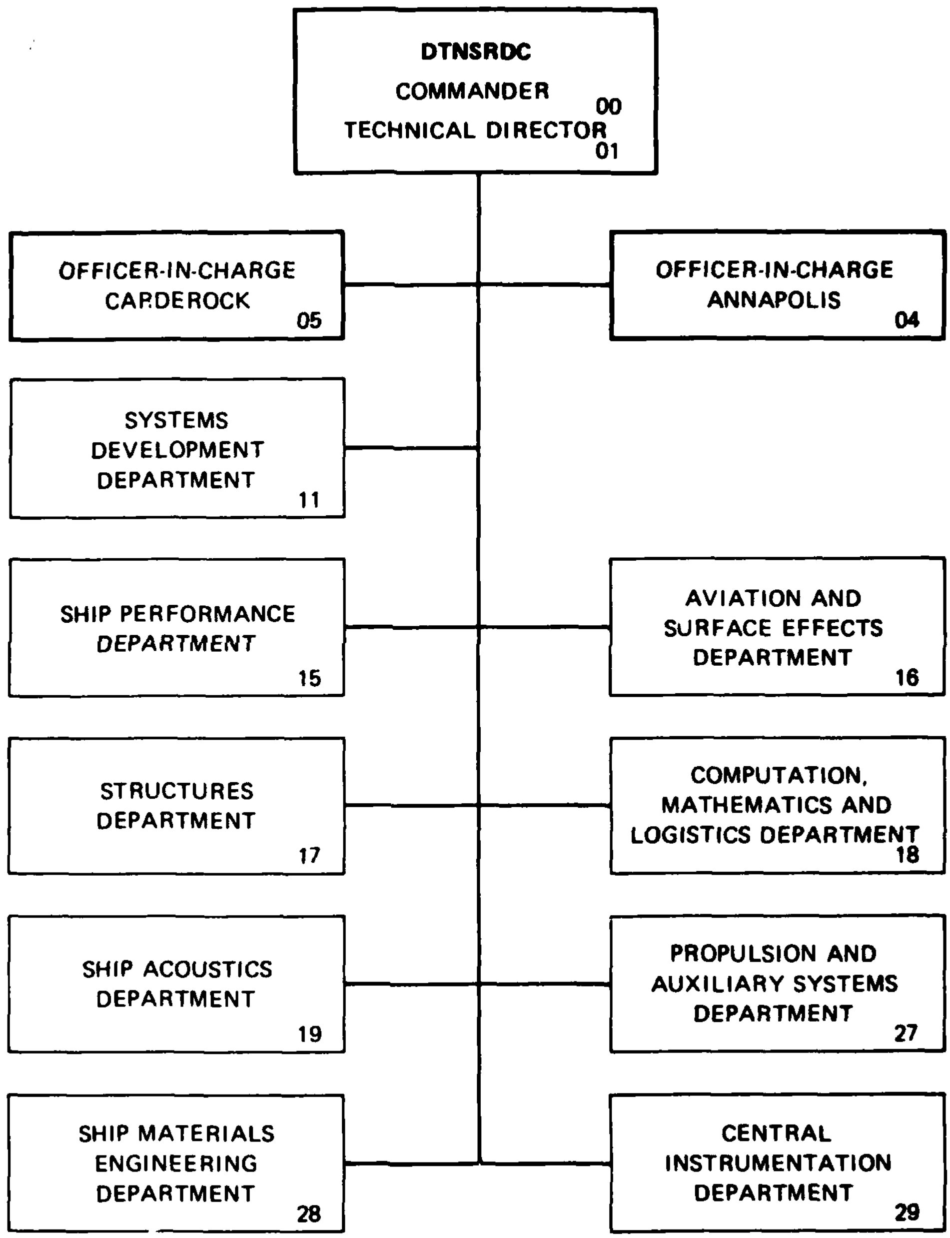
PROPULSION AND AUXILIARY SYSTEMS DEPARTMENT
RESEARCH AND DEVELOPMENT REPORT

June 1981

DTNSRDC/PAS-80/42

STABILITY CHARACTERISTICS OF
EPOXY-IMPREGNATED SUPERCONDUCTING MAGNETS

MAJOR DTNSRDC ORGANIZATIONAL COMPONENTS



UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER DTNSRDC/PAS-80/42	2. GOVT ACCESSION NO. AD-A102 479	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) STABILITY CHARACTERISTICS OF EPOXY-IMPREGNATED SUPERCONDUCTING MAGNETS.		5. TYPE OF REPORT & PERIOD COVERED Research and Development
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) D. J. Waltman, M. J. Superczynski and F. E. McDonald		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS David W. Taylor Naval Ship R&D Center Annapolis, Maryland 21402		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Task Area S0380SL001 Task 16761 Work Unit 1-2706-103
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Sea Systems Command (SEA 05R11) Washington, DC 20362		12. REPORT DATE June 1981
		13. NUMBER OF PAGES 19
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Epoxy Impregnation
Fiber Glass Reinforcement
Superconducting Magnets
Energy Inputs
Magnetic Field
Flux Density

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Epoxy-impregnated superconducting magnets can be subjected to energy inputs from external sources or from stored energy released in the coil composite. If the energy released is sufficiently large, the temperature will rise locally driving the superconductor normal causing a magnet quench. Several superconducting coils were constructed to determine the magnitude and size of disturbances required to cause a quench. These coils were wound from multifilament, niobium titanium conductor

(Continued on Reverse Side)

497615

(Block 20 Continued)

and epoxy impregnated and fiber glass reinforced. Small electrical heaters of various sizes were embedded in the coils to initiate a normal zone. These coils were placed in a background magnetic field ranging in flux density from 0 to 5.5 T, and the energy required to cause a quench was determined as a function of the ratio of operating current to critical current at a constant field. The different size heaters allowed the energy to be distributed over various conductor volumes, and the effects of the energy spatial distribution were determined.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF ABBREVIATIONS

°C	Degrees Celsius
cm	Centimeter
DC	Direct current
ID	Inside diameter
J	Joules
K	Kelvin
kg	Kilogram
kg cm^{-2}	Kilogram per square centimeter
μsec	Microsecond
mJ	Millijoules
mm	Millimeters
MW	Megawatt
NbTi	Niobium titanium
OD	Outside diameter
T	Tesla

NOTATION

B	Magnetic flux density
I	Test magnet operating current
I_b	Background magnet operating current
I_c	Superconductor critical current
T	Tesla unit of magnetic flux density
T_c	Superconductor critical temperature

ABSTRACT

Epoxy-impregnated superconducting magnets can be subjected to energy inputs from external sources or from stored energy released in the coil composite. If the energy released is sufficiently large, the temperature will rise locally driving the superconductor normal causing a magnet quench. Several superconducting coils were constructed to determine the magnitude and size of disturbances required to cause a quench. These coils were wound from multifilament, niobium titanium conductor and epoxy impregnated and fiber glass reinforced. Small electrical heaters of various sizes were embedded in the coils to initiate a normal zone. These coils were placed in a background magnetic field ranging in flux density from 0 to 5.5 T, and the energy required to cause a quench was determined as a function of the ratio of operating current to critical current at a constant field. The different size heaters allowed the energy to be distributed over various conductor volumes, and the effects of the energy spatial distribution were determined.

ADMINISTRATIVE INFORMATION

The work described in this report was performed as part of the Superconductive Machinery Development Project, Task Area S0380SL001, Task 16761, sponsored by the Naval Sea Systems Command (SEA 05R11), Mr. J. Harrison. The work was accomplished under work unit 1-2706-103 in the Electrical Machinery Technology Branch, Electrical Systems Division of the Propulsion and Auxiliary Systems Department at this Center.

INTRODUCTION

The Navy is presently developing the technology base to design and build superconductive motors and generators of up to 58-MW* per propeller shaft for ship propulsion.[1]** A major portion of this program is directed at developing stable and reliable superconducting magnets for use as the field windings of electric propulsion motors and generators. Because of their compact size, ruggedness of construction, and large energy density, epoxy-impregnated, Niobium Titanium (NbTi) superconducting magnets have been selected by the Navy as the prime candidates for the field windings of electric ship drive machinery.

---

* Definitions of abbreviations used are given on page iv.

** A complete list of references appears on page 17.

A significant concern with the shipboard use of fully potted and trained superconducting magnets is their stability when operating in a mechanically hostile environment. Heat energy can be imparted to the superconductor of the magnet from mechanical disturbances such as shipboard shock and vibration that can cause the magnet to quench. To design potted superconducting magnets that can resist these disturbances, the amount of energy needed to quench these magnets at a given field strength must be known as a function of their operating current.

Previous work performed at the Center and reported by Superczynski[2] has provided stability measurement data for a fully potted superconducting test coil. But since a separate magnet to provide a constant background field was not available, these measurements resulted in stability data for different operating currents and corresponding different magnetic field strengths. For magnet design, it is desirable to know the stability of a magnet as a function of its operating current at different, but fixed, values of magnetic field. This knowledge is needed for machine design because the magnetic field strength is usually a specified requirement, and the magnet designer selects the operating current based on space restrictions and stability requirements. To obtain constant field stability data, an experiment has been performed to measure the energy to quench of a small test magnet that is operated in the controlled field of a separate background magnet.

TEST MAGNET CONSTRUCTION

The test magnets used in the experiment are small, epoxy-impregnated solenoidal coils wound with rectangular wire having 180 NbTi superconducting filaments with a 1-cm twist pitch in a copper matrix. The wire has a cross section of 0.685 by 0.521 mm, a copper to superconductor ratio of 1.8 to 1, and is coated with formvar insulation approximately 0.02 mm thick. All the test coils constructed for stability measurements were wound with wire manufactured from the same billet to assure uniform wire characteristics for all the test magnets. In addition, the coils were consecutively wound on an aluminum mandrel to ensure that the coils would be of identical construction including the same potting material and curing procedure.

The test magnets, as shown in Figure 1, have five layers of winding, 88 electrical turns total, and have overall measurements of 18.76-cm outside diameter (OD), 18.00-cm inside diameter (ID), and 1.40-cm length. The coils were wound on the aluminum mandrel with an initial layer of dry 0.089-mm-thick fiber glass cloth. After the initial layer of fiber glass cloth was applied, the first layer of wire was wound on the cloth. This procedure was repeated for each layer of winding until five layers of winding have been built up. The outside surface of the coil was then wound with a 5 layer fiber glass overwrap. A thin sheet of metal was placed around the outer diameter of the coil with sufficient clearance to allow penetration of the epoxy when the coil is potted. During the winding of the test coils, bare wire, constantan heaters, 0.08 cm in diameter and of various

lengths, were imbedded in each coil. As shown in Figure 1, each heater was located between the second and third winding layers, and centered along the length of the coil. The finished coil assembly was then placed in a vacuum potting chamber and impregnated with an epoxy mix composed of Ciba 6004 epoxy resin with equal parts of Lindride 12 and Lindride 16 hardeners.* This epoxy mix contained, by weight, 100 parts of resin to 85 parts of hardener and was degassed and heated to 65°C prior to potting the coil. After the coils had been potted, they were cured at a temperature of 85°C and 7.03 kg/cm^2 of pressure for a period of 8 hr. Upon completion of the curing process, the coils were removed from the potting chamber, machined to a final outside diameter of 18.76 cm, and then removed from the winding mandrel.

TEST MAGNET AND BACKGROUND MAGNET ASSEMBLY

The assembly of a test magnet in the inner bore of the background magnet is shown in Figure 2. The superconducting background magnet has an inside diameter of 19.4 cm, an outside diameter of 24.0 cm, and is 9.4 cm long. The test magnet is concentrically located at the mid-length of the inner bore of the background magnet. The operating load lines for the test magnet and the background magnet at the heater location of the test magnet are shown in Figure 3. Also shown in Figure 3 is the measured short sample characteristic for the superconducting wire of the test magnet. To provide a constant total magnetic flux density, B, for various values of test coil transport current, I, the operating current of the background, I_b, was determined from the combined load-line equations of the two magnets:

$$0.0015\,I + 0.0589\,I_b = B \qquad (1)$$

To obtain a desired constant total magnetic field for each value of test coil operating current, the operating current of the background magnet was computed using the above equation, and the background magnet was operated at this value.

*CIBA 6004 is manufactured by Ciba Products Co., Summit, New Jersey. Lindride 12 and Lindride 16 hardener are manufactured by Lindan Chemical Inc., Columbia, South Carolina. Trade names are used to define material and does not imply any endorsement of particular products by this Center or the U.S. Navy.

EXPERIMENTAL METHOD

For the experiments to measure the energy to quench, the test coil and background coil assembly was placed in a cryogenic dewar and cooled from room temperature to 4.2 K using liquid helium. After both magnets reached their superconducting state, they were each energized to predetermined operating currents using separate power supplies as shown in Figure 4.

The objective of the experiment was to measure the minimum energy required to quench the test coil at constant magnetic field and for various values of test coil operating current. Therefore for any selected value of magnetic field strength and test coil operating current for which energy to quench measurements would be made, the operating current of the background magnet was computed from the combined load-line equation previously given as Equation (1). The operating current of the background magnet was ramped up to its calculated value, and then the test magnet operating current was raised to a predetermined percentage of its critical current. To measure the energy to quench at another value of test coil operating current, the operating current of the background magnet was recomputed and adjusted to this value to maintain a constant total magnetic field. Therefore, using this procedure, the measurements of the energy to quench the test magnet could be obtained as a function of its operating current and at fixed magnetic field strength.

To quench the test coil with a known amount of electrical energy, a pulse generator and power amplifier system, as illustrated in Figure 4, was used to deliver a single pulse of electrical current to the resistor heater imbedded in the test coil. A calibrated oscilloscope was used to measure the amplitude and width of the electrical pulse with the pulse generator and power amplifier operating in the repetitive mode and driving a dummy load equivalent to the heater load. From these measurements, the instantaneous power of the pulse to be delivered to the heater was computed, and the product of this power and the time duration of the pulse was used as the measurement of the heat energy to be imparted to the test coil. After the pulse amplitude and the width had been selected, the pulse generator was operated in its manual and single-pulse mode, and the power amplifier output was connectd to the heater of the test coil.

The actual test procedure involved setting the pulse width to a fixed value of 100 μsec and adjusting the pulse amplitude to obtain the minimum energy required to quench the coil. For each run of the experiment, the amplitude of the constant width pulse was initially set to a value estimated to be less than that needed to quench the magnet. The amplitude of the pulse was then increased in small voltage increments until the test magnet quenched. A time interval of at least 1 minute was allowed between each pulse that did not quench the magnet so that the heat energy imparted to the test coil could dissipate to the helium bath. After the test magnet suffered a quench, it was re-energized to a desired operating current, and its temperature was allowed to stabilize for several minutes before continuing the experiments.

DISCUSSION OF RESULTS

The results of the experiments to measure the minimum energy required to quench the test magnet at constant field and at an operating temperature of 4.2 K are shown in Figures 5 and 6. In Figure 5, the minimum energy to quench the test coil containing a 1.27-cm heater is plotted as a function of the ratio of the test coil operating current to its critical current (I/I_c) for the magnet field strengths shown. Figure 6 is also a plot of the minimum energy to quench as a function of I/I_c and for the magnetic fields shown, but for a test coil containing a heater 0.635 cm in length. As both figures show, the magnitude of the energy to quench at a constant field value varies greatly over the range of I/I_c of 0.1 to 0.95 for which measurements were obtained. The shape of each curve is similar to the results obtained by Superczynski where the magnetic field strength also varied with the I/I_c values. But the results of the constant field measurements of energy to quench do show a flattening of the curve shape in the I/I_c range of 0.2 to 0.8 as predicted by Superczynski[2] for a condition of constant field. However, the constant field results do not show a trend of constant energy to quench for the lower values of I/I_c as predicted by the theoretical work of Wilson. Instead, the measured results indicate that the stability of a potted superconducting magnet at any magnetic field strength can be greatly improved by operating it at a transport current that is a small percentage (I/I_c of 0.3 or less) of its critical current.

A definite trend that can be observed in the results for both the test coil with the 1.27-cm heater and the test coil with the 0.635-cm heater is a decrease in the minimum energy to quench for increasing values of magnetic flux density up to 5T. As an example using the results of Figure 5, the energy to quench at I/I_c of 0.5 varies from 1.5 X 10^{-3} J at a flux density of 2T to 7.5 X 10^{-4} J at 5T. This decrease in minimum energy to quench with increasing field strength appears to be the result of the decrease in the critical temperature of the NbTi superconductor. In Figure 7, the critical temperature of the NbTi conductor is plotted as a function of I/I_c for magnetic flux densities of 2T and 5T. The superconductor critical temperature for I/I_c of 0.5 at 2T is 6.3 K, and at 5T the critical temperature is 5.7 K. Therefore the difference in critical temperature from the 4.2 K bath temperature is 2.1 K at 2T and decreases to 1.5 K at 5T. The reason for the small decrease, as shown in Figure 6, or no decrease, as shown in Figure 5, of the energy to quench for the flux densities from 5T to 5.5T is not known.

Comparing the measurements of the energy to quench the test coil having the 1.27-cm heater to those of the test coil containing the 0.635-cm heater, it can be observed that in the I/I_c range of 0.3 to 0.9 the coil with the 1.27-cm heater required approximately twice the energy to quench than the coil with the 0.635-cm heater. The magnitude of the energy density of the heat disturbance is the same in both coils, and this result indicates that the energy density of the heat disturbance produces the quench in a potted superconducting magnet.

CONCLUSIONS

The results of the measurements of the energy required to quench a potted superconducting magnet are in agreement with the results reported by Superczynski.[illegible] These results show that a potted superconducting magnet has a region of maximum stability at low values of I/I_c, a region of high instability at the higher values of I/I_c, and that its stability decreases approximately linearly in the I/I_c region of 0.3 to 0.8. It is evident that in the design of a magnet for a particular field strength that stability is sacrificed whenever current density is maximimized, and an engineering tradeoff decision between stability and current density must be made in each design. Using the results of Figures 5 and 6, a magnet designer, attempting to maximize current density but desiring to maintain good stability, would probably select an operating current that would correspond to a I/I_c value in the region of 0.5 to 0.8. In Figures 8 and 9, the measurements of the minimum energy to quench versus I/I_c in the region of 0.5 to 0.8 have been replotted using a linear scale for energy. These curves show that the decrease in energy to quench (or magnet stability) is approximately linear for increasing values of I/I_c and that the sacrifice in stability for increasing values of I/I_c is at its minimum in this region.

From tradition and experience, the stability design margin for potted magnets has been set to be 20% from the 4.2 K short sample along the magnet load line. When this margin is compared with the stability results obtained from the measurements of the energy to quench at constant field, it is found that the 20% stability margin may be a conservative limit. For example, the preliminary designs of the 6.5T magnets at the 30 MW propulsion motor size have included a 20% stability margin in field and current. This margin in both field and current translates to an actual I/I_c of approximately 0.5 at the 6.5T magnetic flux density. Using the curves of Figures 8 and 9, the data results indicate that it may be practical to operate these magnets at an I/I_c of up to 0.7 which translates to a margin along the load line from a short sample of approximately 10%.

Another result of the measurements of the energy required to quench a potted superconducting magnet is that high field magnets are less stable than low field magnets for the same ratio of I/I_c. As Figures 5 and 6 or Figures 8 and 9 show, a magnet operating at a magnetic flux density of 2T is more stable than a magnet operating at 5T. Although this result can be related to the higher values of critical temperature (as shown in Figure 7) for magnets operating at 2T as compared to 5T, further work is required to fully explain the measured relationship.

In the area of planned work, an effort will be undertaken to relate the measured stability of potted superconducting magnets to the minimum propagating zone concept developed by Wipf.[4] The MPZ is defined as the norml zone size for which joule heating produced in the normal zone is equal to the heat removed from the zone by conduction and cooling. Therefore, a definite relationship should exist between the calculated size of the minimum propagating zone and the measured minimum energy to quench, since both describe the stability of a superconducting coil. Work is presently being performed to determine this relationship and will be the subject of a future report.

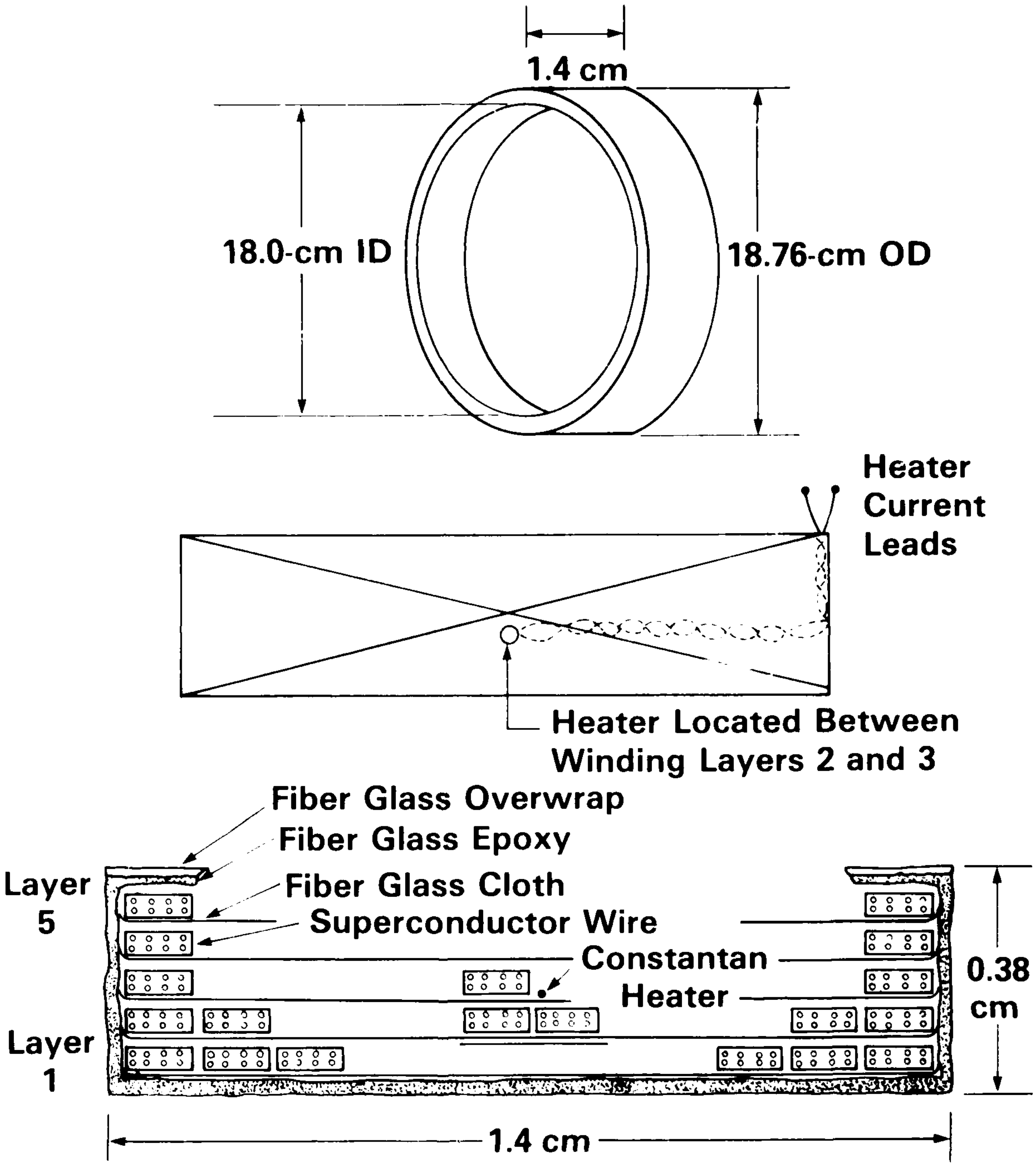


Figure 1. Superconducting Test Coil Construction and Heater Location

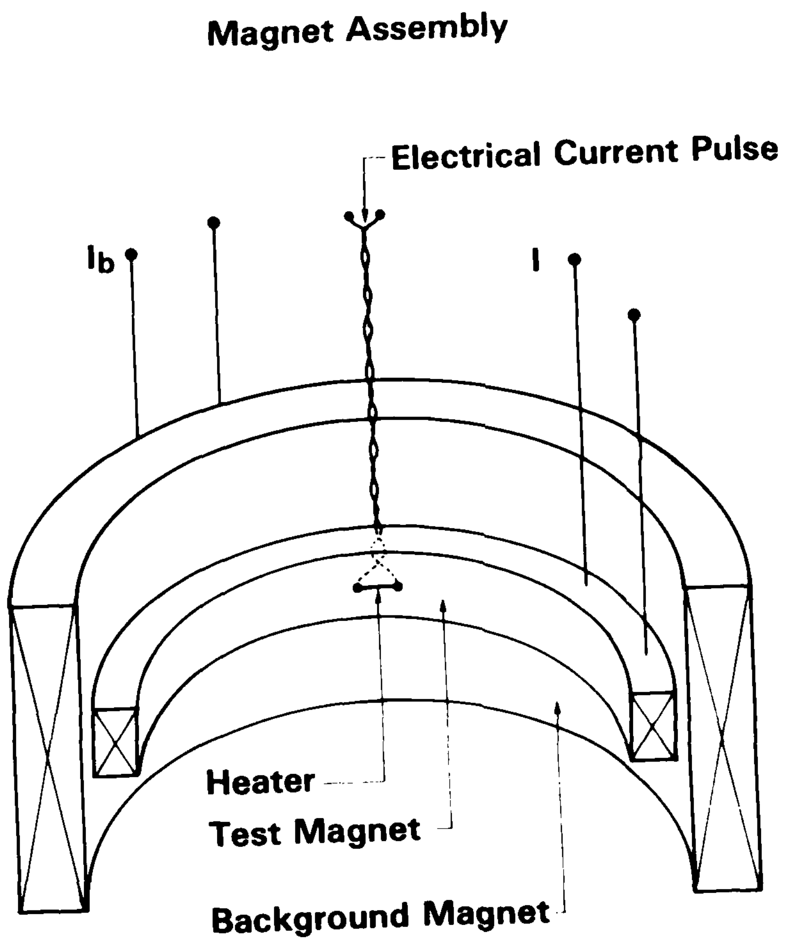


Figure 2 — Magnet Assembly for Energy to Quench Measurements

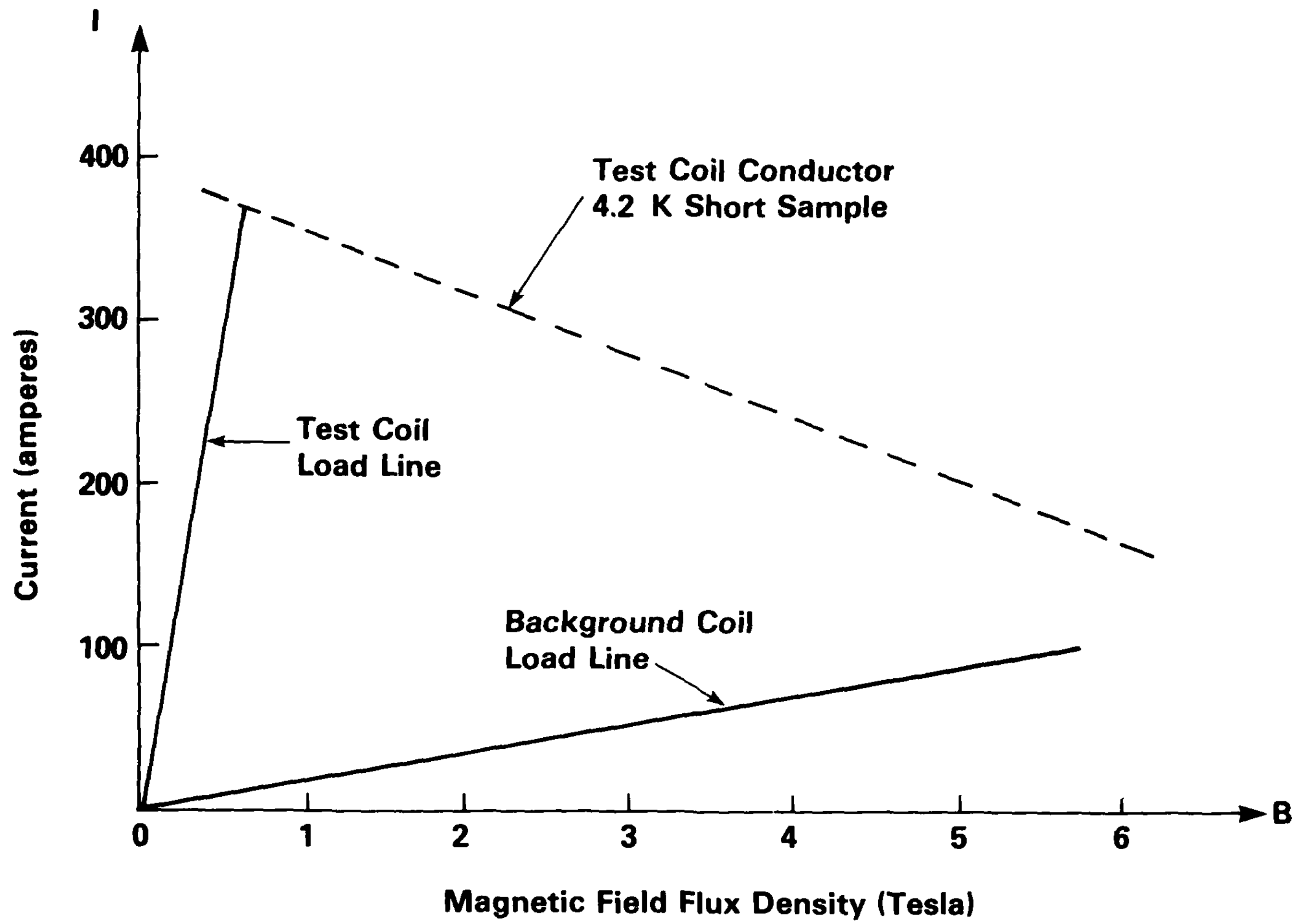


Figure 3 — *Test and Background* Magret Load Lines and Test Coil Conductor Short Sample Characteristics

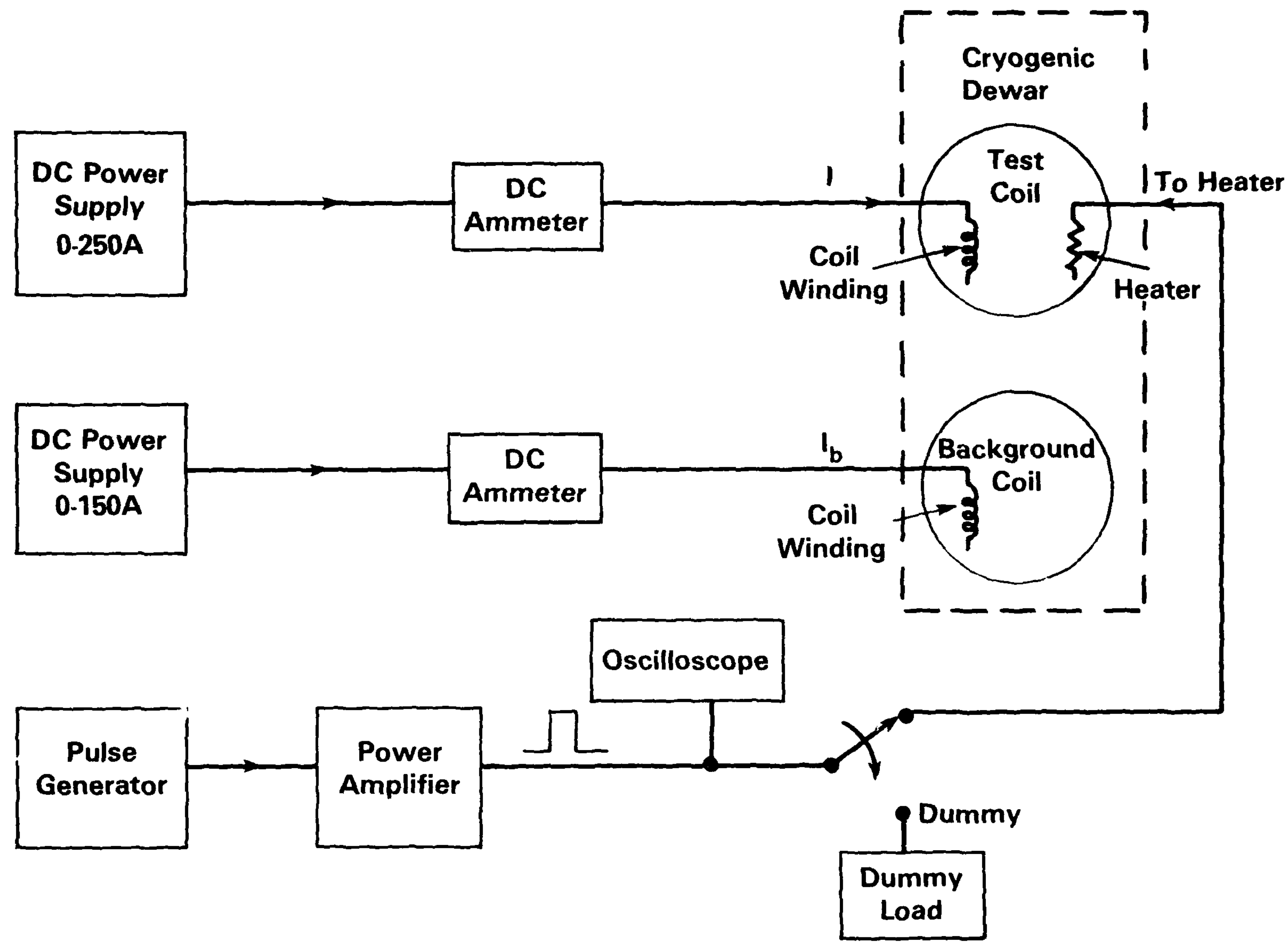


Figure 4 Experiment Instrumentation and Power Supply Connection Diagram

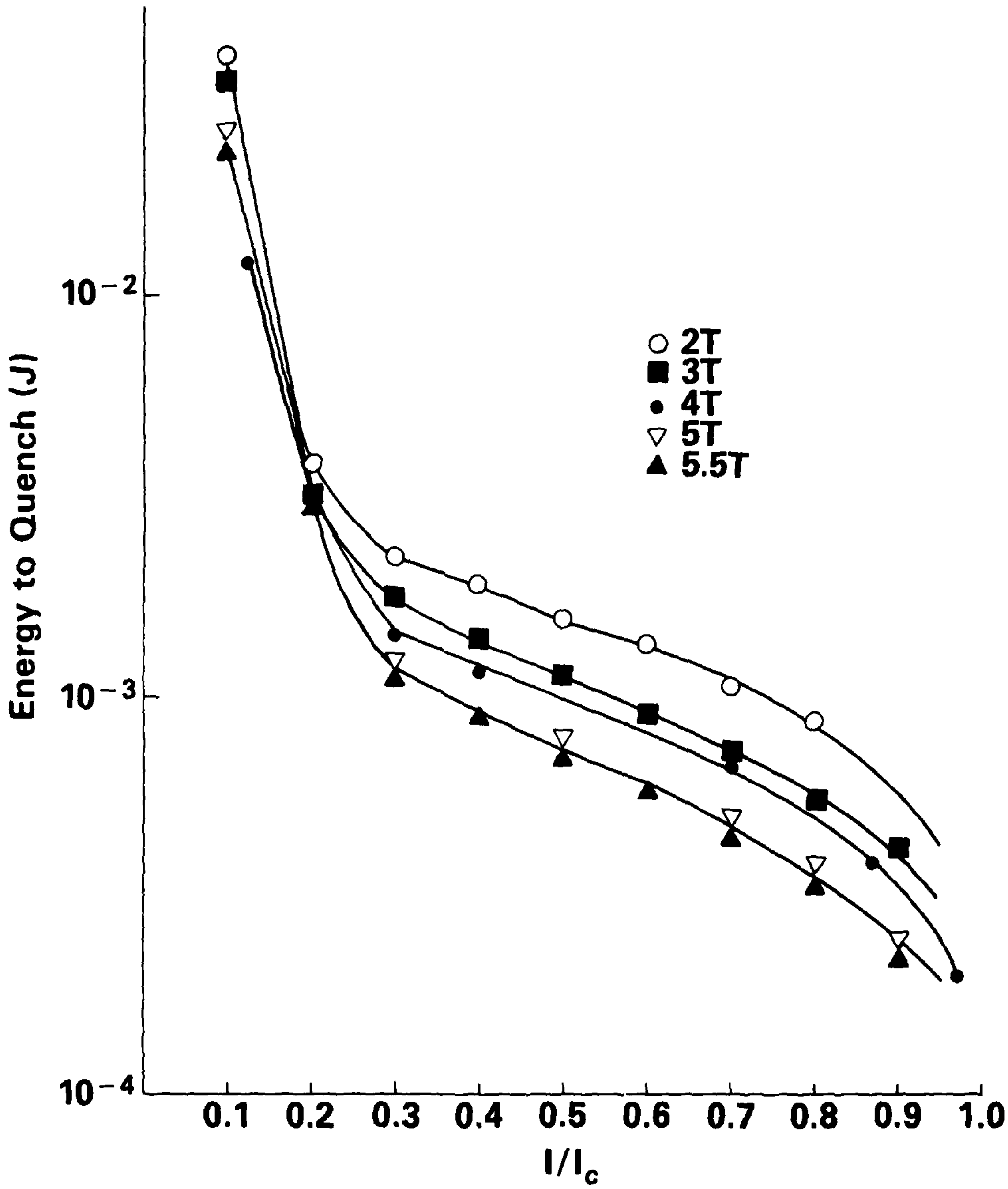


Figure 5 — Energy to Quench Versus I/I_c for Test Coil Continuing a 1.27-Centimeter Heater

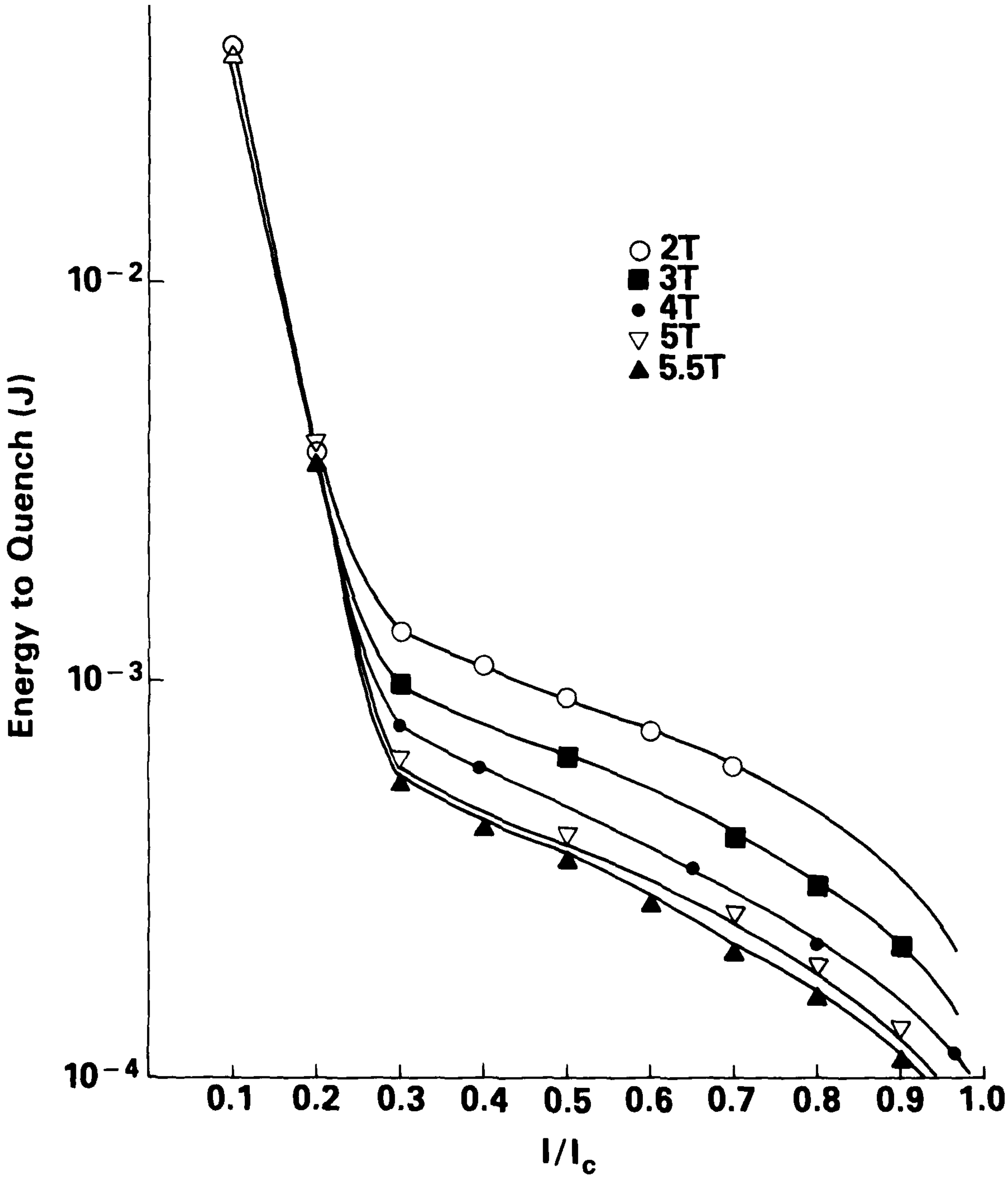


Figure 6 -- Energy to Quench Versus I/I_c for Test Coil Containing a 0.635-Centimeter Heater

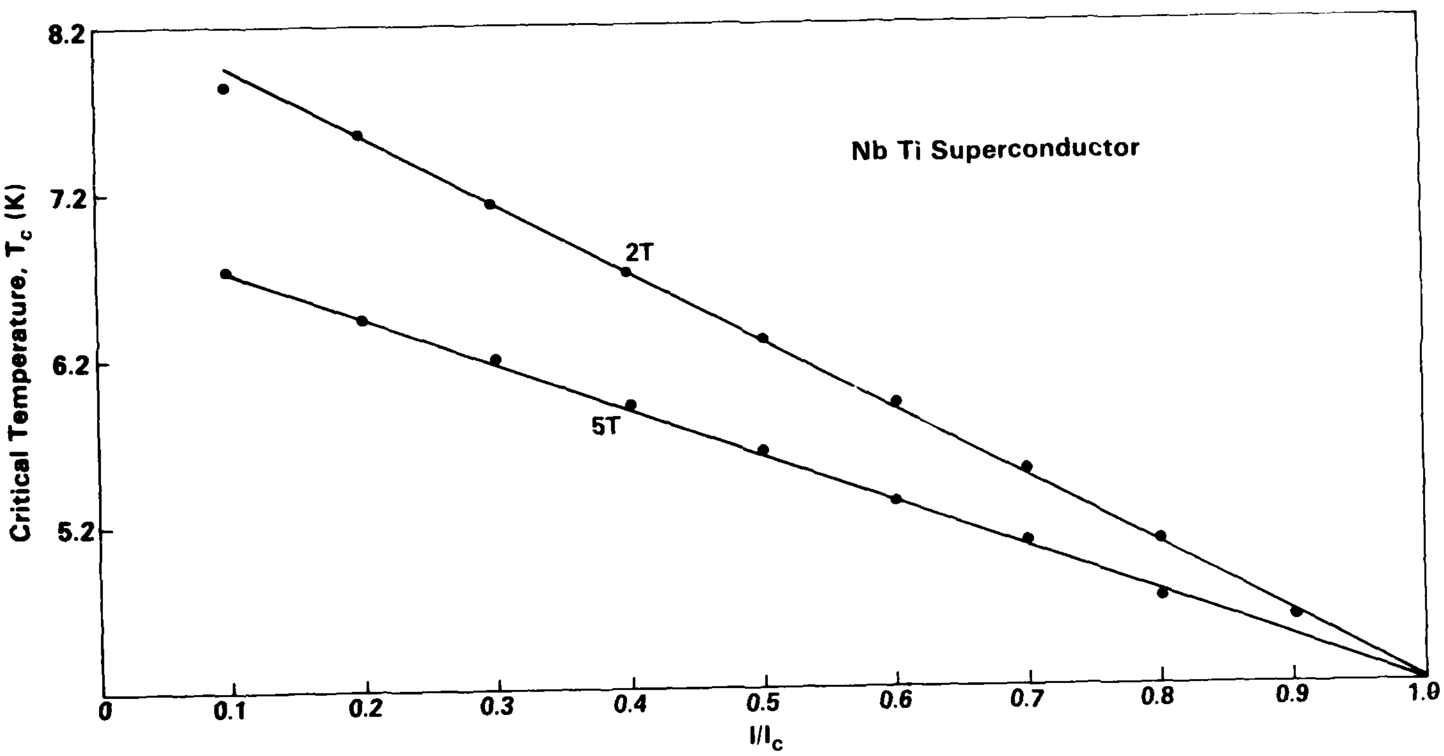


Figure 7 — Critical Temperature, T_c, of Niobium Titanium Superconductor for 2T and 5T Magnetic Flux Densities

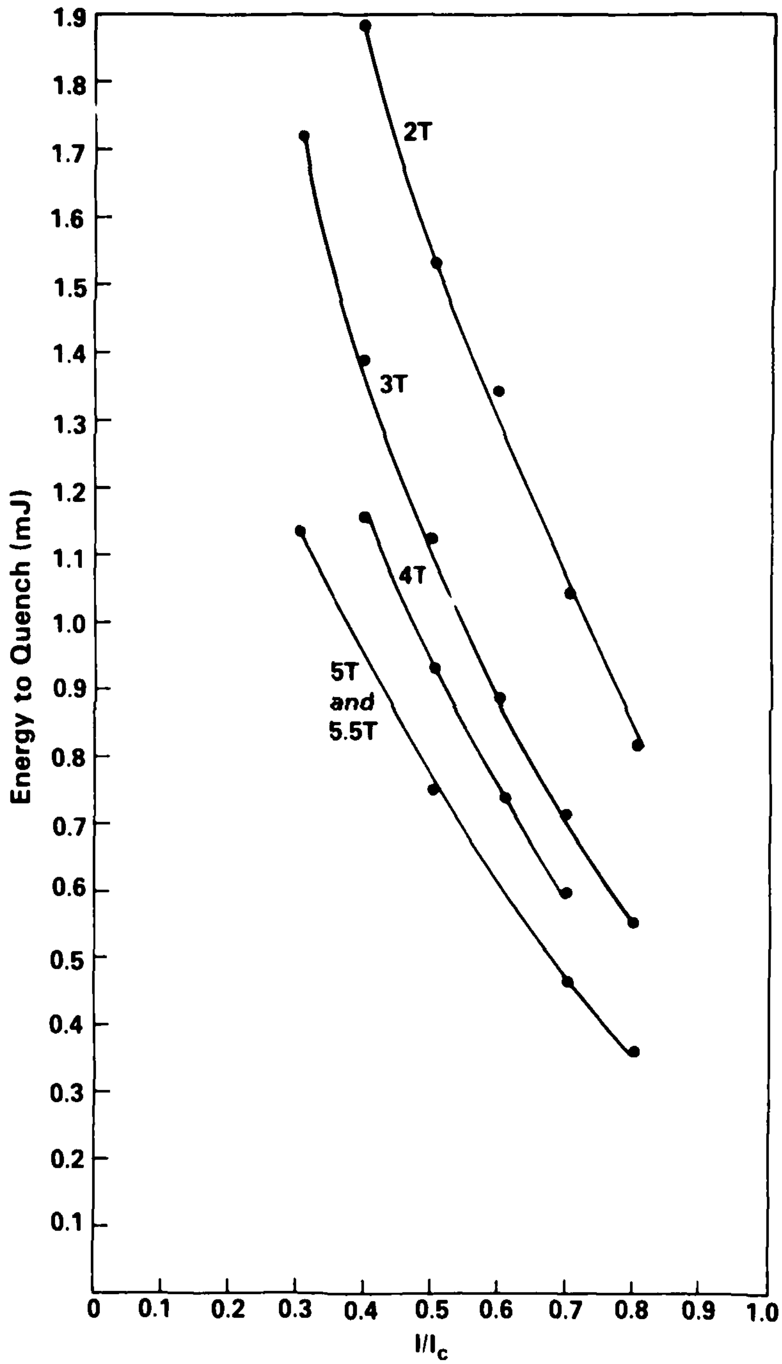


Figure 8 -- Linear Plot of Energy to Quench Versus I/I_c for Test Coil with 1.27-Centimeter Heater

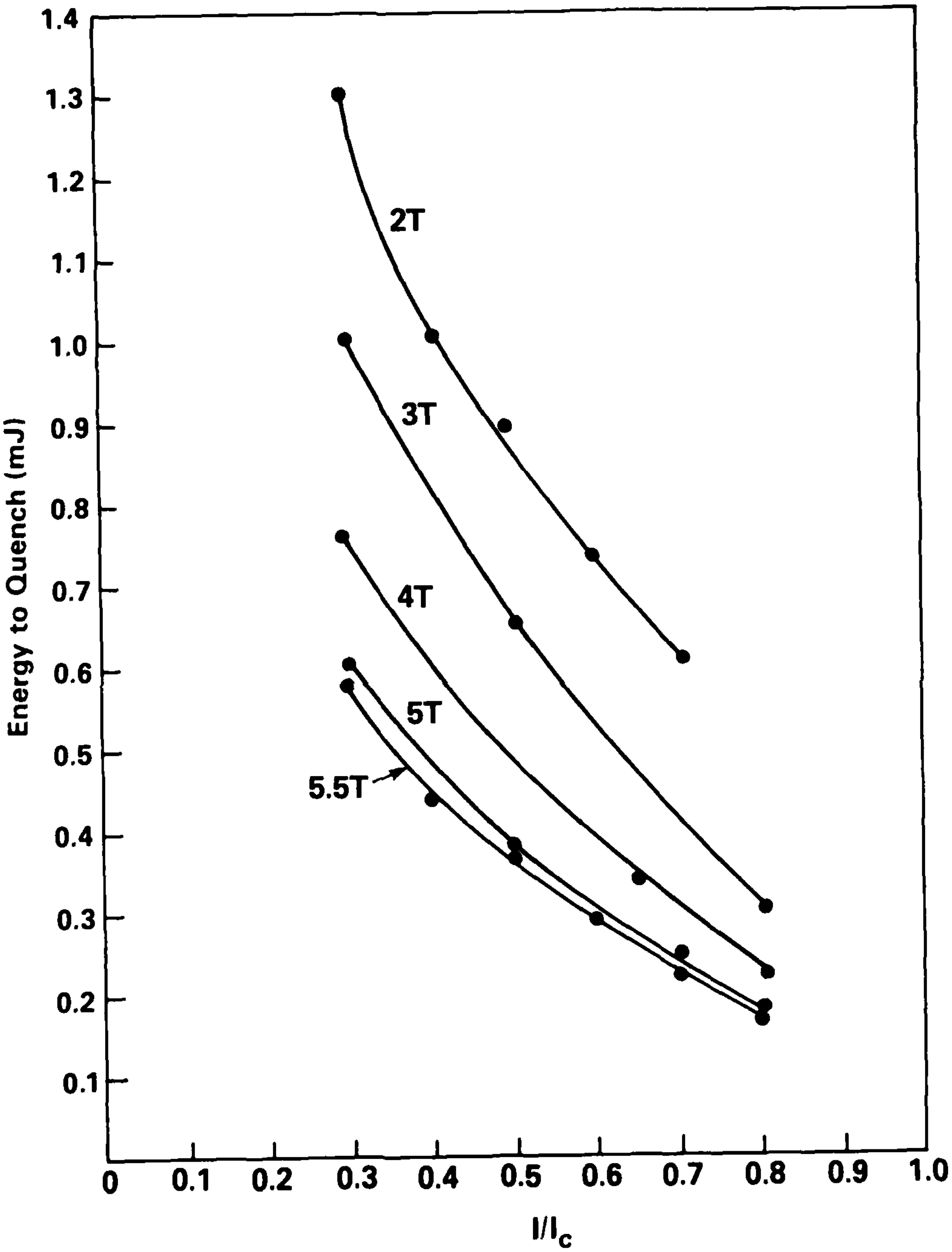


Figure 9 — Linear Plot of Energy to Quench Versus I/I_c for Test Coil with 0.635-Centimeter Heater

REFERENCES

1. Doyle, T. J., *et al,* "Navy Superconductive Machinery Program," paper prepared at the Spring Meeting/STAR Symposium (26-29 Apr 1978).

2. Superczynski, M. J., "Heat Pulses Required to Quench a Potted Superconducting Magnet," *IEEE Transactions on Magnetics,* Vol. Mag-15, No. 1 (Jan 1979).

3. Wilson, M. N., "Stabilization of Superconductors for Use in Magnets," *IEEE Transactions on Magnetics,* Vol. Mag-13, No. 1 (Jan 1977).

4. Wipf, S. L., "Stability and Degradation of Superconducting Current-Carrying Devices," Los Alamos Scientific Laboratory Report LA-7275 (Dec 1978).

INITIAL DISTRIBUTION

Copies	
5	NAVSEA 1 SEA 05R11 1 SEA 5432 1 SEA 03R 2 SEA 99612
2	ONR 1 Code 473 1 Code 211
1	Westinghouse Electric Company R&D Center 1310 Beulah Road Pittsburgh, PA 15235 Attn: D. L. Green
1	General Electric Company Corporate R&D P.O. Box 43 Schenectady, NY 12301 Attn: R. A. Marshall
1	AiResearch Manufacturing Company 2525 West 190th Street Torrance, CA 90509 Attn: W. Rumer
12	DTIC

CENTER DISTRIBUTION

Copies	Code
1	2706
2	271
18	2712
1	522.1
2	5231

PRECEDING PAGE BLANK-NOT FILMED

DTNSRDC ISSUES THREE TYPES OF REPORTS

1. DTNSRDC REPORTS, A FORMAL SERIES, CONTAIN INFORMATION OF PERMANENT TECHNICAL VALUE. THEY CARRY A CONSECUTIVE NUMERICAL IDENTIFICATION REGARDLESS OF THEIR CLASSIFICATION OR THE ORIGINATING DEPARTMENT.

2. DEPARTMENTAL REPORTS, A SEMIFORMAL SERIES, CONTAIN INFORMATION OF A PRELIMINARY, TEMPORARY, OR PROPRIETARY NATURE OR OF LIMITED INTEREST OR SIGNIFICANCE. THEY CARRY A DEPARTMENTAL ALPHANUMERICAL IDENTIFICATION.

3. TECHNICAL MEMORANDA, AN INFORMAL SERIES, CONTAIN TECHNICAL DOCUMENTATION OF LIMITED USE AND INTEREST. THEY ARE PRIMARILY WORKING PAPERS INTENDED FOR INTERNAL USE. THEY CARRY AN IDENTIFYING NUMBER WHICH INDICATES THEIR TYPE AND THE NUMERICAL CODE OF THE ORIGINATING DEPARTMENT. ANY DISTRIBUTION OUTSIDE DTNSRDC MUST BE APPROVED BY THE HEAD OF THE ORIGINATING DEPARTMENT ON A CASE-BY-CASE BASIS.